Properties of Weakly-decaying Bottom Baryons, Ξ_b^- and Ω_b^-, at CDF

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We present properties of weakly decaying bottom baryons, Ξ_b^- and Ω_b^-, using 4.2 fb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV, and recorded with the Collider Detector at Fermilab. We report the observation of the Ω_b^- through the decay chain $\Omega_b^- \to J/\psi\,\Omega^-$, where $J/\psi \to \mu^+\,\mu^-$, $\Omega^- \to \Lambda\,K^-$, and $\Lambda \to p\,\pi^-$. Significance of the observed signal is estimated to be 5.5 Gaussian standard deviations. The Ω_b^- mass and lifetime are measured to be $6054.4 \pm 6.8(\text{stat.}) \pm 0.9(\text{syst.})$ MeV/c^2 and $1.13^{+0.53}_{-0.40}(\text{stat.}) \pm 0.02(\text{syst.})$ ps, respectively. In addition, the mass and lifetime of the Ξ_b^- baryon are measured to be $5790.9 \pm 2.6(\text{stat.}) \pm 0.8(\text{syst.})$ MeV/c^2 and $1.56^{+0.27}_{-0.25}(\text{stat.}) \pm 0.02(\text{syst.})$ ps, respectively. Under the assumption that the Ξ_b^- and Ω_b^- are produced with similar kinematic distributions as the Λ_b^0 baryon, we measure $\frac{\sigma(\Xi_b^-)\mathcal{B}(\Xi_b^- \to J/\psi\,\Xi^-)}{\sigma(\Lambda_b^0)\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda)} = 0.167^{+0.037}_{-0.025}(\text{stat.}) \pm 0.012(\text{syst.})$ and $\frac{\sigma(\Omega_b^-)\mathcal{B}(\Omega_b^- \to J/\psi\,\Omega^-)}{\sigma(\Lambda_b^0)\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda)} = 0.045^{+0.017}_{-0.012}(\text{stat.}) \pm 0.004(\text{syst.})$ for baryons produced with transverse momentum in the range of $6 - 20$ GeV/c.

1. Introduction

Until recently, tests of quark model predictions of b-baryon spectroscopy have been limited to only Λ_b^0 [1]. With accumulation of large data sets from the Tevatron, some of the other predicted baryons, Ξ_b^- [2, 3] and $\Sigma_b^{(*)}$ [4] have been observed and are in good agreement with the quark model predictions.

In this paper, we report the observation of an additional heavy baryon, the doubly-strange Ω_b^- ($|ssb\rangle$), and the measurement of its mass, lifetime, and relative production rate compared to the Λ_b^0 production. Observation of this baryon has been previously reported by the DØ Collaboration [5]. However, the analysis presented here measures a mass of the Ω_b^- significantly lower than Ref. [5].

The measurements reported here are made using $p\overline{p}$ collisions at a center of mass energy of 1.96 TeV acquired by the Collider Detector at Fermilab (CDF II) and based on a data sample corresponding to an integrated luminosity of 4.2 fb^{-1}. The Ω_b^- candidates are reconstructed through the decay chain $\Omega_b^- \to J/\psi\,\Omega^-$, where $J/\psi \to \mu^+\mu^-$, $\Omega^- \to \Lambda\,K^-$, and $\Lambda \to p\,\pi^-$. Charge conjugate modes are implied throughout this paper. Mass, lifetime, and production rate measurements are also reported for the Ξ_b^-, through the similar decay chain $\Xi_b^- \to J/\psi\,\Xi^-$, where $J/\psi \to \mu^+\mu^-$, $\Xi^- \to \Lambda\,\pi^-$, and $\Lambda \to p\,\pi^-$. The production rates of both the Ξ_b^- and Ω_b^- are measured with respect to the Λ_b^0, which is observed through the decay chain $\Lambda_b^0 \to J/\psi\,\Lambda$, where $J/\psi \to \mu^+\mu^-$, and $\Lambda \to p\,\pi^-$.

To build confidence in the analysis procedure, all the measurements made here are also performed on better known $b-$hadron states $B^0 \to J/\psi\,K^*(892)^0$, $K^*(892)^0 \to K^+\pi^-$; $B^0 \to J/\psi\,K_s^0$, $K_s^0 \to \pi^+\pi^-$; and $\Lambda_b^0 \to J/\psi\,\Lambda$, $\Lambda \to p\,\pi^-$ for comparison with other experiments. The $K^*(892)^0$ mode provides a large B^0 sample. The K_s^0 is reconstructed from tracks that are significantly displaced from the collision, similar to the final state tracks of the Ξ_b^- and Ω_b^-. The Λ_b^0, on the other hand, is a suitable reference state for relative production rate measurements, since it is the largest sample of reconstructed b-baryons.

2. Event Reconstruction

We employ multi-stage kinematic fits of final state charged particle trajectories to infer intermediate and ultimate parent hadron decay vertices. Fig. 1 depicts this complex procedure for the Ω_b^-. The events are

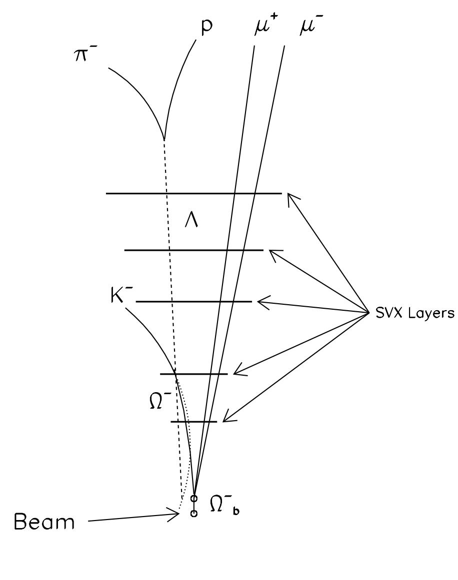

Figure 1: An illustration (not to scale) of the $\Omega_b^- \to J/\psi\,\Omega^-$, $J/\psi \to \mu^+\,\mu^-$, $\Omega^- \to \Lambda\,K^-$, and $\Lambda \to p\,\pi^-$ final state as seen in the view transverse to the beam direction.

recorded using the CDF di-muon trigger which is dedicated to collecting $J/\psi \to \mu^+\mu^-$ samples.

The event reconstruction begins with a selection of well-measured $J/\psi \to \mu^+\mu^-$ candidates. This data sample provides approximately 2.9×10^7 J/ψ candidates, measured with an average mass resolution of ~ 20 MeV/c^2.

The K_s^0, $K^*(892)^0$, and Λ candidates are reconstructed from all tracks with $p_T > 0.4$ GeV/c found in the CDF central outer tracker (COT), that are not associated with muons in the J/ψ reconstruction. Candidate selection for these neutral states is based upon the mass calculated for each oppositely charged track pair, which is required to fall within ± 30, ± 20, and ± 9 MeV/c^2 of the nominal mass for the $K^*(892)^0$, K_s^0, and Λ, respectively. Backgrounds to the K_s^0 and Λ are reduced by requiring the flight distance of the K_s^0 and Λ with respect to the primary vertex to be greater than 1.0 cm. Approximately 3.6×10^6 Λ candidates are found with with $p_T(\Lambda) > 2.0$ GeV/c.

Events containing a Λ candidate are searched for $\Lambda\,\pi^-$ or $\Lambda\,K^-$ combinations consistent with the decay process $\Xi^- \to \Lambda\,\pi^-$ or $\Omega^- \to \Lambda\,K^-$ by assigning pion or kaon mass to the remaining tracks. A $p_T(K^-) >$ 1.0 GeV/c requirement is imposed for our Ω^- sample, which reduces the combinatorial background by 60%, while reducing the Ω^- signal predicted by our Monte Carlo simulation by 25%. In addition, the flight distance of the Λ candidates with respect to the reconstructed decay vertex of the $\Xi^-(\Omega^-)$, and the flight distance from the primary vertex of the Ξ^- and Ω^- candidates is required to exceed 1.0 cm. Kinematic reflections are removed from the Ω^- sample by requiring that the combinations consistent with Ξ^- decay, when the candidate K^- track is assigned the mass of the π^-. Any ambiguities for the proper track assignments of the hadrons are resolved examining the $P(\chi^2)$ of the vertex fits. Shown in Fig. 2 are approximately 41 000 Ξ^- and 3500 Ω^- candidates found in this data sample. $\Lambda\,\pi^-$ or $\Lambda\,K^-$ combinations within ± 9 and ± 8 MeV/c^2 of the nominal Ξ^- and Ω^- masses are selected for b-hadron reconstruction. Shown also are the signal and sideband regions (shaded) and the wrong-sign combinations (dashed histograms).

Finally b-hadron candidates are reconstructed by combining the K and hyperon candidates with the J/ψ candidates which involves fitting the full four-track or five-track state with constraints appropriate for each decay topology and intermediate hadron state. Specifically, the muon pair mass is constrained to the nominal J/ψ mass [1] and the neutral K or hyperon candidate is constrained to originate from the J/ψ decay vertex. In addition, the fits that include the charged hyperons constrain the Λ candidate tracks to the nominal Λ mass [1], and the Ξ^- and Ω^- candidates to their respective nominal masses [1]. The Ξ_b^- and Ω_b^- mass resolutions obtained from simulated events are found to be approximately 12 MeV/c^2, a

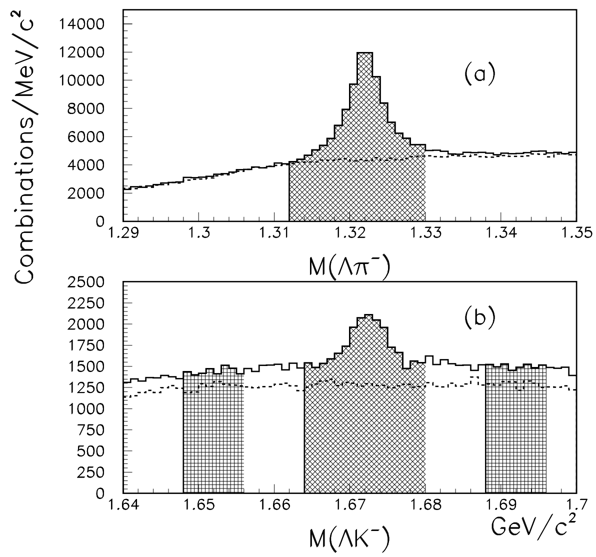

Figure 2: The invariant mass distributions of (a) $\Lambda\,\pi^-$ combinations and (b) $\Lambda\,K^-$ combinations in events containing J/ψ candidates. Shaded areas indicate the signal and sideband regions used for Ξ^- and Ω^- candidates. Wrong-sign combinations are also shown as dashed histograms.

value that is comparable to the mass resolution obtained with the CDF II detector for other b-hadrons with a J/ψ meson in the final state [6].

3. Observation of the Decay $\Omega_b^- \to J/\psi\,\Omega^-$

The $J/\psi\,\Omega^-$ mass distribution with $ct > 100\,\mu$m is shown in Fig. 3(b). The decay time (ct) requirement is imposed on all candidates in the mass measurements to reduce the prompt background to the b-hadrons. The significance of the structure seen in the $J/\psi\,\Omega^-$ mass distribution is evaluated with a simultaneous fit to the mass and lifetime distributions which is maximized for two different conditions. The first maximization allows all parameters to vary in the fit. The second one fixes the signal fraction to 0.0. The value of $-2\ln\mathcal{L}$ obtained for the null hypothesis is higher than the value obtained for the fully varying fit by 37.3 units. We interpret this as equivalent to a χ^2 with three degrees of freedom, which has a probability of occurrence of 4.0×10^{-8}, or a 5.5σ fluctuation. Fig. 4 shows sigma contours in $-2\ln\mathcal{L}$ of the $J/\psi\,\Omega^-$ mass and decay time simultaneous fit. We interpret the $J/\psi\,\Omega^-$ mass distributions shown in Fig. 3(b) to be the observation of a weakly decaying resonance, with a width consistent with the detector resolution. We treat this resonance as observation of the Ω_b^- baryon

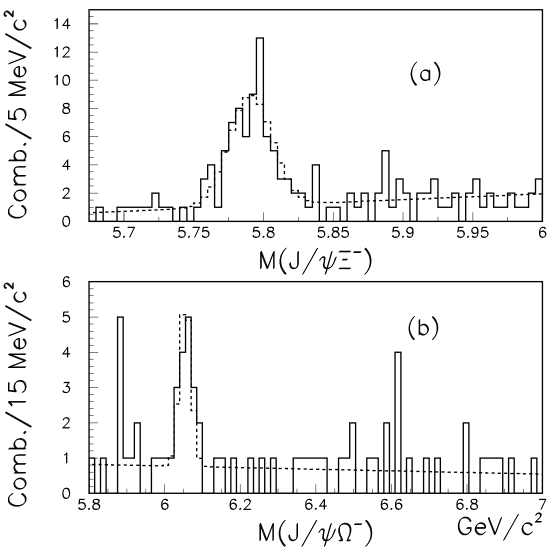

Figure 3: The invariant mass of (a) $J/\psi\,\Xi^-$ and (b) $J/\psi\,\Omega^-$ candidates with $ct > 100\,\mu$m. The projections of the unbinned mass fit are indicated by the dashed histograms.

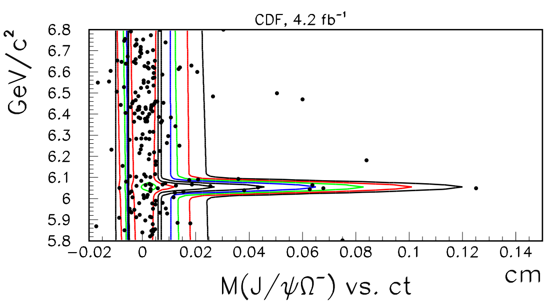

Figure 4: Sigma contours in $-2\ln\mathcal{L}$ of the $J/\psi\,\Omega^-$ mass and decay time simultaneous fit.

through the decay process $\Omega_b^- \to J/\psi\,\Omega^-$.

4. Ξ_b^- and Ω_b^- Property Measurements

The mass distributions of the Ξ_b^- and Ω_b^- candidates are shown in Fig. 3, along with fit projections. The results of these fits as well as those from the 3 reference samples are listed in Table I. Systematic uncertainties for the Ξ_b^- and Ω_b^- masses are largely driven by our B^0 mass measurements, and are estimated to be 0.8 and 0.9 MeV$/c^2$, respectively. Fig. 5 shows our measurement of the Ξ_b^- and Ω_b^- masses along with those from the DØ Collaboration and the theoretical predictions [7]. Our Ω_b^- mass result is consistent with the theoretical predictions and in disagreement with

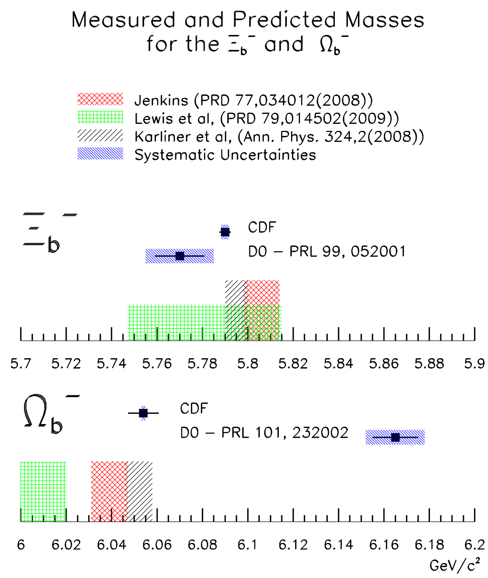

Figure 5: A comparison between the mass measurements and theoretical predictions.

the DØ measurement [5].

We measure b-hadron lifetimes by a technique which is insensitive to the detailed lifetime characteristics of the background. This allows for the lifetime calculation to be done on a relatively small sample, since a large number of events is not needed for background modeling. The data are binned in ct, and the number of signal candidates in each ct bin is compared to the value that is expected for a particle with a given lifetime and measurement resolution. Fig. 6 shows Ξ_b^- and Ω_b^- candidates in ct bins (solid histograms) and their fit value (dashed histograms). The estimates of the systematic uncertainties are obtained from the B^0 lifetime measurements. The results of the fits for the lifetimes of the baryons and reference samples are listed in Table I.

Finally we present the measurements of the Ξ_b^- and Ω_b^- production rates relative to the plentiful Λ_b^0, where we measure ratios of cross section times branching fractions. The acceptances and efficiencies of the three baryon states are obtained as a function of p_T from the detector simulation. We use the observed p_T distribution of Λ_b^0 production to obtain the total efficiency for the Ξ_b^- and Ω_b^- states. The yields of the baryons extracted from the lifetime fits are listed in Table I, along with our measurements of the Ξ_b^- and Ω_b^- relative production rates. The total relative systematic uncertainty on the production ratios and 7% for the Ξ_b^- and 9% for the Ω_b^-.

Table I Measured b-hadrons properties.

Resonance	**Candidates**	**Mass (MeV/c^2)**	$c\tau$ **(μm)**	$\frac{\sigma\mathcal{B}}{\sigma(\Lambda_b^0)\mathcal{B}(\Lambda_b^0\to J/\psi\,\Lambda)}$
$B^0(J/\psi\,K^*(892)^0)$	17520 ± 305	5279.2 ± 0.2	453 ± 6	-
$B^0(J/\psi\,K_s^0)$	9424 ± 167	5280.2 ± 0.2	448 ± 7	-
Λ_b^0	1934 ± 93	5620.3 ± 0.5	472 ± 17	-
Ξ_b^-	66^{+14}_{-9}	$5790.9 \pm 2.6 \pm 0.8$	$468^{+82}_{-74} \pm 0.06$	$0.167^{+0.037}_{-0.025} \pm 0.012$
Ω_b^-	16^{+6}_{-4}	$6054.4 \pm 6.8 \pm 0.9$	$340^{+160}_{-120} \pm 0.04$	$0.045^{+0.017}_{-0.012} \pm 0.004$

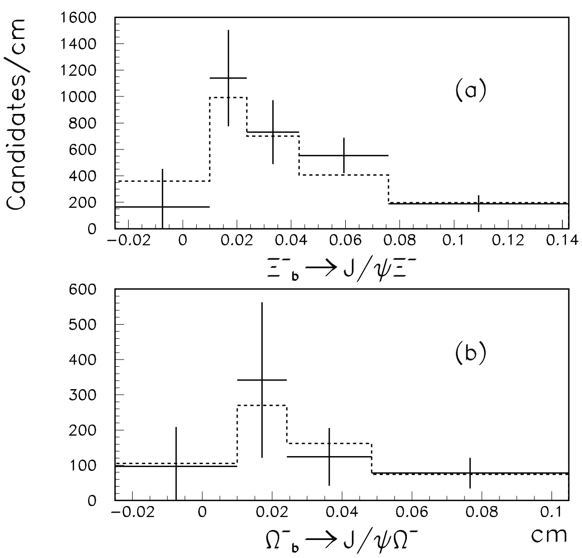

Figure 6: The solid histograms represent the number of (a) $\Xi_b^- \to J/\psi\,\Xi^-$ and (b) $\Omega_b^- \to J/\psi\,\Omega^-$ candidates found in each ct bin. The dashed histogram is the fit value.

5. Conclusions

Using a 4.2 fb^{-1} data sample collected with the CDF II detector at the Tevatron we have observed a signal of 16^{+6}_{-4} Ω_b^- candidates, with a significance equivalent to 5.5σ. The mass, lifetime and relative production rates of the Ω_b^- and Ξ_b^- are measured with the best level of precision to date. Three additional samples of B^0 and Λ_0 have been used as reference samples for cross-checks and to motivate the systematics estimation. The masses of these baryons are in good agreement with the theoretical predictions, while the Ω_b^- mass is at odds with the previously reported measurement. More measurements are necessary to resolve this observed discrepancy.

Acknowledgments

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